BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 08028

SUBJECT: Performance Comparison of Nuclear and Chemical Lunar Shuttles - Case 105-6

DATE: August 14, 1970

FROM: D. J. Osias

ABSTRACT

Payload performance of nuclear and chemical lunar shuttles is compared, including the effects of earth-moon transfer time, plane change maneuvers, one-way missions, two-stage shuttles, and aerobraked return to earth orbit. It is seen that for large payload requirements, around 120,000 pounds to lunar orbit, the nuclear shuttle is lighter, even if the chemical shuttle is staged or aerobraked. Higher velocity missions and higher payloads tend to further increase the advantage of the nuclear shuttle. However, lower payloads tend to favor the chemical shuttle, and for payloads of 50,000 pounds or less, chemical shuttles with high mass fractions can compete by using the more complex mission profiles. Also, a shuttle sized for relatively small payloads can deliver occasional large payloads by using a one-way mission.

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MEMORANDUM FOR FILE

I. INTRODUCTION

The NASA Integrated Plan of July 1969 indicated the need for a reusable nuclear shuttle (RNS) to operate in cislunar space, primarily between low earth orbit and lunar orbit. The RNS was to be sized for a payload capability of 120,000 pounds delivered to lunar orbit with no payload returned. For such payloads, the nuclear shuttle could have substantial performance advantages over a chemical shuttle, and consequently only the nuclear cislunar shuttle has been studied. However, for smaller payload requirements, chemical stages look relatively more attractive because the propellant mass fraction of the nuclear stage decreases substantially as its size decreases. Hence, as the payload requirement is lowered, there will be a point where the chemical shuttle becomes competitive. If a shuttle is sized for small payloads, occasional large payloads can still be delivered either by a one-way mission (refueling the spent stage in lunar orbit for return) or by staging two or more shuttles. It seems advisable then, to size the shuttle for the more frequently required payloads rather than for the maximum payload expected during the program. In this regard, a payload capacity substantially smaller than 100,000 pounds may prove to be desirable.

Complex mission modes can increase the performance of chemical shuttles. For example, the ratio of payload to gross weight can be increased by using staged shuttles or by using aerobraking to decelerate the shuttle into low earth orbit at the completion of the mission. These complex missions are not suitable for use with nuclear shuttles for the following reasons: In order to deliver the same payload with staged shuttles, the shuttles must be considerably smaller. Small nuclear stages, however, have such poor mass fractions that the performance benefits of staging are almost entirely lost. In addition, aerobraking of nuclear stages is considered to be a high risk maneuver due to the radioactivity hazard, although no study of the hazards has been made. It is recognized, however, that the feasibility of aerobraking even a chemical reusable stage may not be within current technical state of the art.

The calculations presented in this memorandum show quantitatively the effect of the above operational modes on performance of lunar shuttles. The effect of plane change maneuvers during the lunar departure phase of the mission and the effect of earth-moon transfer time are included. Calculations for two stage shuttles assume identical stages, regardless of the resulting intermediate orbit.

II. DISCUSSION

All missions considered operate between a 260 nm circular earth orbit and a 43 nm circular lunar orbit. Ideal velocities for earth departure and arrival were derived for mean earth moon distance, but the velocity requirements for lunar maneuvers were taken from Reference 1, which assumes maximum earth-moon separation. Reference 1 was also used to obtain the velocity requirements for plane change maneuvers during lunar departure.

The various operational modes include 72 hour and 108 hour earth-moon transfers, 0° and 90° plane change maneuvers, single and two-stage shuttles, aerobraked chemical shuttles, and one way trips for large payloads. The 0° plane change missions limit the shuttle return opportunities to only two per month, whereas the 90° plane change capability permits return to earth at any time. The plane changes are accomplished using a 3-burn lunar departure with an intermediate elliptical orbit. The nominal mission is taken as a round trip mission with 72 hour transfers each way, no plane changes, a single stage shuttle, and propulsive braking at earth arrival. The actual modes that were considered (combinations of the above choices) are given in Figure 1, which is also a legend for the performance graphs presenting the results of this study.

Gravity velocity losses were included only for earth departure maneuvers of the nuclear shuttle. All other vehicles and other maneuvers of the RNS were assumed to be made with thrust-to-weight ratios high enough for gravity losses to be negligible.

A. Chemical

Chemical vehicles were assumed to have propellant mass fractions between 0.87 and 0.91. Aerobraked stages were considered with mass fractions raging from 0.91 to as low as 0.80. An Isp of 460 seconds was used for all chemical propulsion.

B. Nuclear

The inert weights of the baseline nuclear stages were calculated from the scaling law: $W_{inert} = 36{,}775 + 0.1846\ W_{prop}$.

This relationship was derived from Lockheed's weight breakdown for their baseline modular RNS (Reference 2) using this author's estimates of the weight scaling of each subsystem. The weights of a man-rated radiation shield, propellant residuals, and avionics were added to Lockheed's weights where necessary. Optimistic nuclear inert weights were derived by reducing the baseline nuclear weight by 10%.

Aftercooling of the Nerva engine was taken into account by reducing the Isp used in the calculations. A real Isp of 825 seconds was assumed, and this value was reduced to 805 seconds using data in Reference 3, in which an Isp of 480 seconds for aftercooling propellant is indicated. For one typical mission analyzed in Reference 3, 42% of all the aftercooling propellant is used after earth departure, and 5.7% of all propellant is used for aftercooling. Since ΔV added when the vehicle is away from perigee is relatively less useful, 2/3 of the earth departure aftercooling was discarded. Aftercooling following other burns was assumed to be useful, with an Isp of 480 seconds. The mission analyzed in Reference 3 and used here for calculating the effective Isp is an 8 burn mission involving plane changes during both lunar arrival and lunar departure.

Regardless of the size of the nuclear shuttle and whether staged vehicles are used, only one Nerva I engine (75,000 lbs thrust) is operated at any time.

III. RESULTS

Performance comparisons are presented in two formats:

1. Gross weights are shown as a function of λ (for chemical stages) for a fixed payload capability for each of the several operational modes. Three different payload mixes are considered: 120,000 lbs to lunar orbit with 20,000 lbs returned; 50,000 lbs to lunar orbit with 20,000 lbs returned; and 20,000 lbs delivered each way.

2. For a fixed gross weight, earth to moon payloads are shown as a function of λ (for chemical stages) for each of the operational modes. The return payload is fixed at either 20,000 lbs or zero. Three different gross weights are used, corresponding to the gross weights of nuclear stages for delivering each of the three payload mixes noted above.

The performance of the shuttles is shown in Figures 2-12. The letter labeling each curve refer to the legend in

Figure 1, which describes the trajectory associated with each curve. The letters of the legend refer to both chemical and nuclear shuttles. Nuclear performance is not shown as a function of λ because λ is dependent upon gross weight. Instead, two scaling laws are used, denoted as baseline and optimistic, which are derived for man-rated vehicles and are listed in Figure 1. The payloads or gross weights of nuclear shuttles are shown as tick marks on the left side of the graphs, labeled with letters that denote the trajectories.

Figures 2 through 12 show that for large payloads (120,000 pounds out and 20,000 pounds back) the nuclear shuttle is superior to the chemical shuttle, even if the chemical vehicle is staged or uses aerobraking for the earth orbit insertion maneuver. For small payloads (20,000 lbs each way), the chemical shuttle with a high mass fraction is superior for the lower velocity missions and for all missions if the chemical shuttle is staged or aerobraked. However, the single stage chemical shuttle performance is highly sensitive to mass fraction and mission velocity requirements.

In comparing the nuclear and chemical shuttle performance, it may not be sufficient to consider only which vehicle delivers the most payload. Since different development programs and different operational procedures are involved, any decision based on relative performance capabilities must also consider the magnitude of the improvement offered by the superior system. The performance calculations reported here show that a chemical shuttle using two stage operation or aerobraking may be capable of roughly the same performance as a nuclear stage, especially for payloads of less than 50,000 pounds. Consequently, the decision between nuclear and chemical cislunar shuttles should include consideration of payload requirements, expected traffic, operational complexity and hazards, and development costs, as well as the relative payload performance of the two shuttles.

1013-DJO-ab

D. J. Osias

Attachment

REFERENCES

1. E. D. Webb, "Three Impuse Transfer from Lunar Orbits", Americal Astronomical Society, Preprint 66-134, July, 1966.

2. "Nuclear Flight Systems Definition Study, Final Briefing", Lockheed Missiles and Space Co., LMSC-A968323, May 19, 1970.

3. J. W. Altseimer, G. F. Mader, and J. J. Stewart, "Operating Characteristics and Requirements for the Nerva Flight Engine", AIAA Paper number 70-676, June, 1970.

FIGURE 1

LEGEND FOR GRAPHS OF SHUTTLE PERFORMANCE

A. 72-hour transfers, no plane change (baseline case).

B. 72-hour transfers, plus 90° plane change using 24-hour ellipse on return only.

C. 60-hour transfer plus 90° plane change using 12-hour ellipse on return (72-hour transfer outbound).

D. 108-hour transfers (both ways) with no plane change.

E. Two-stage shuttle, 72-hour transfers, no plane change.

F. Two-stage shuttle, 60-hour transfer plus 12-hour, 90° plane change on return (72-hour transfer outbound).

G. Payload for two shuttles, each with gross weight of Wg, 72-hour transfers, no plane change.

H. One way payload (outbound), 108-hour transfer.

J. Payload with aerobraking at EOI, 72-hour transfers, no plane change.

K. Payload with aerobraking at EOI, 60-hour transfer plus 12 hr, 90° plane change on return (72-hour transfer outbound).

Baseline Nuclear: $W_{inert} = 36{,}775 + 0.1846\ W_{propellant}$

Optimistic Nuclear: W_{inert} = 90% of Baseline inert weight

FIGURE 2
LUNAR SHUTTLE GROSS WEIGHTS
FOR 120K/20K PAYLOADS

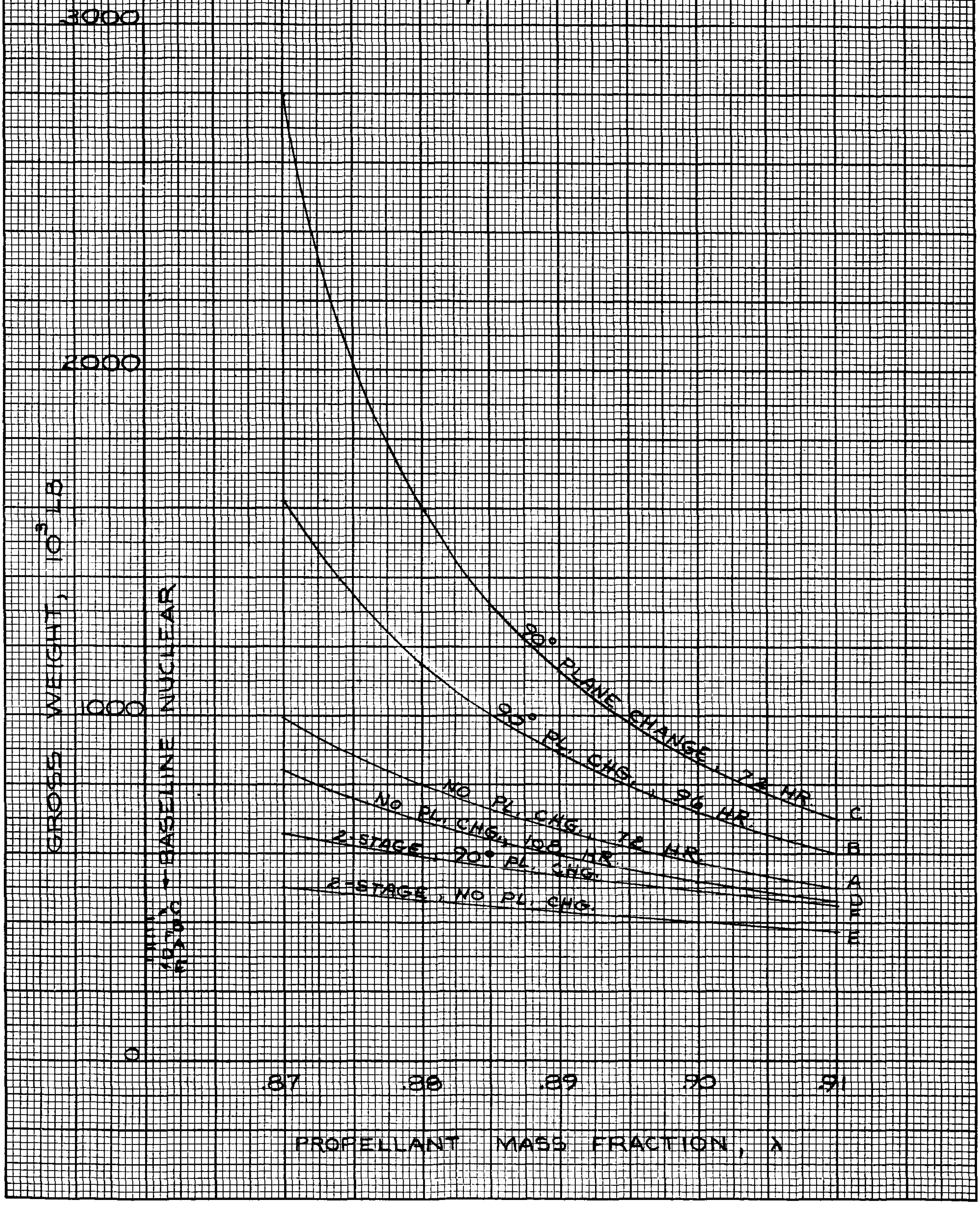


FIGURE 3
LUNAR SHUTTLE
GROSS WEIGHTS
FOR 50K/20K PAYLOADS

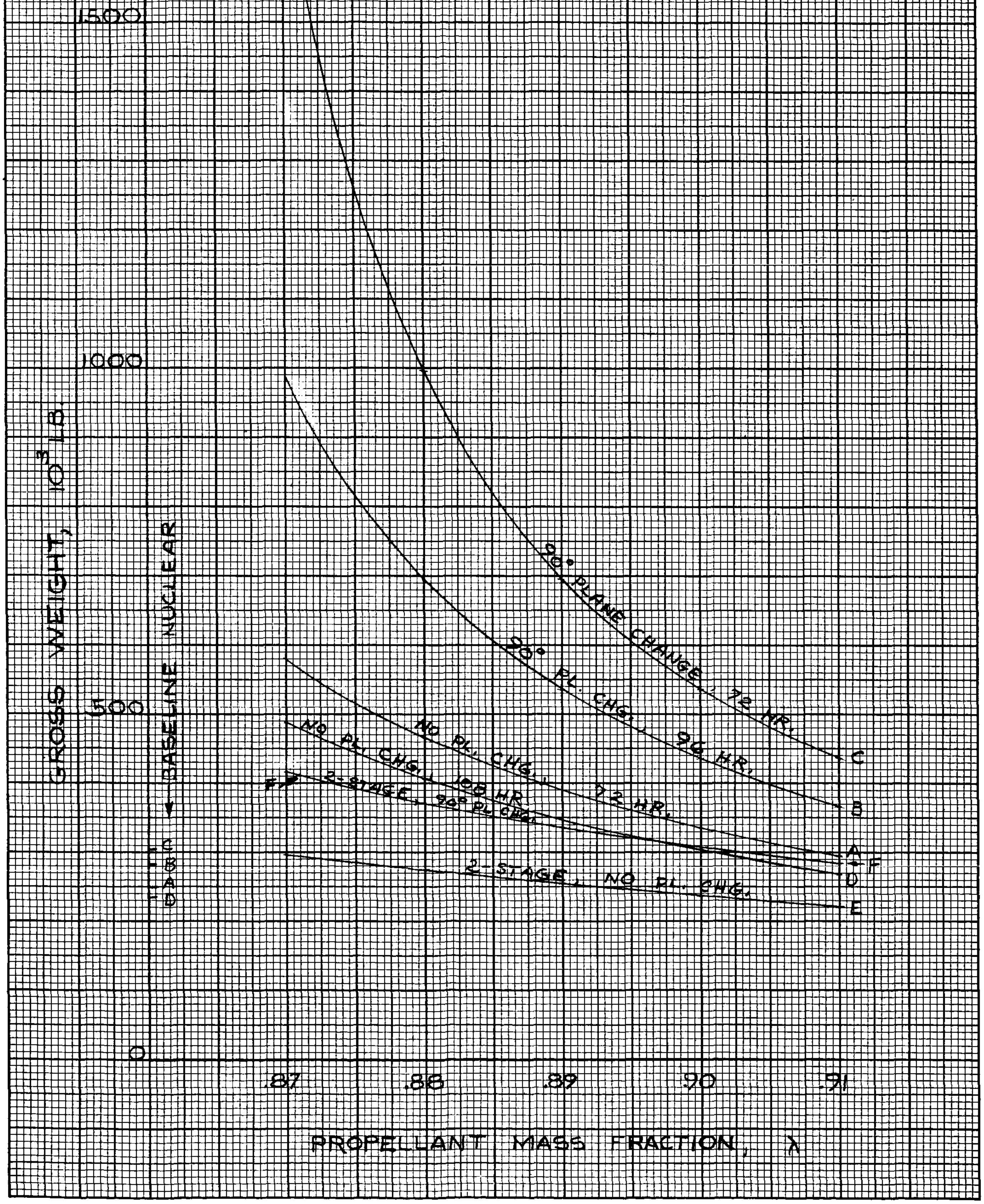
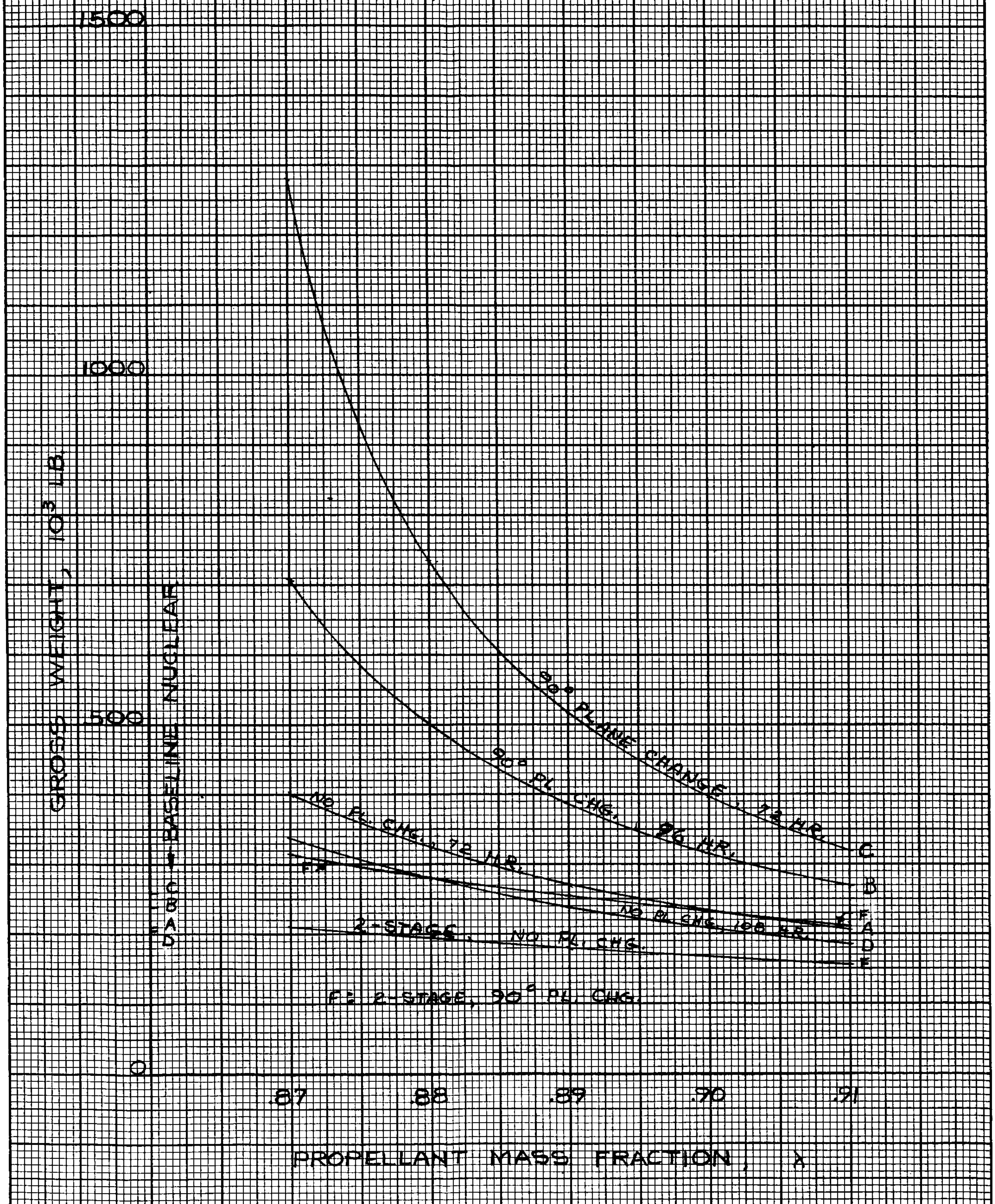


FIGURE 4
LUNAR SHUTTLE GROSS WEIGHTS
FOR 20K/20K PAYLOADS



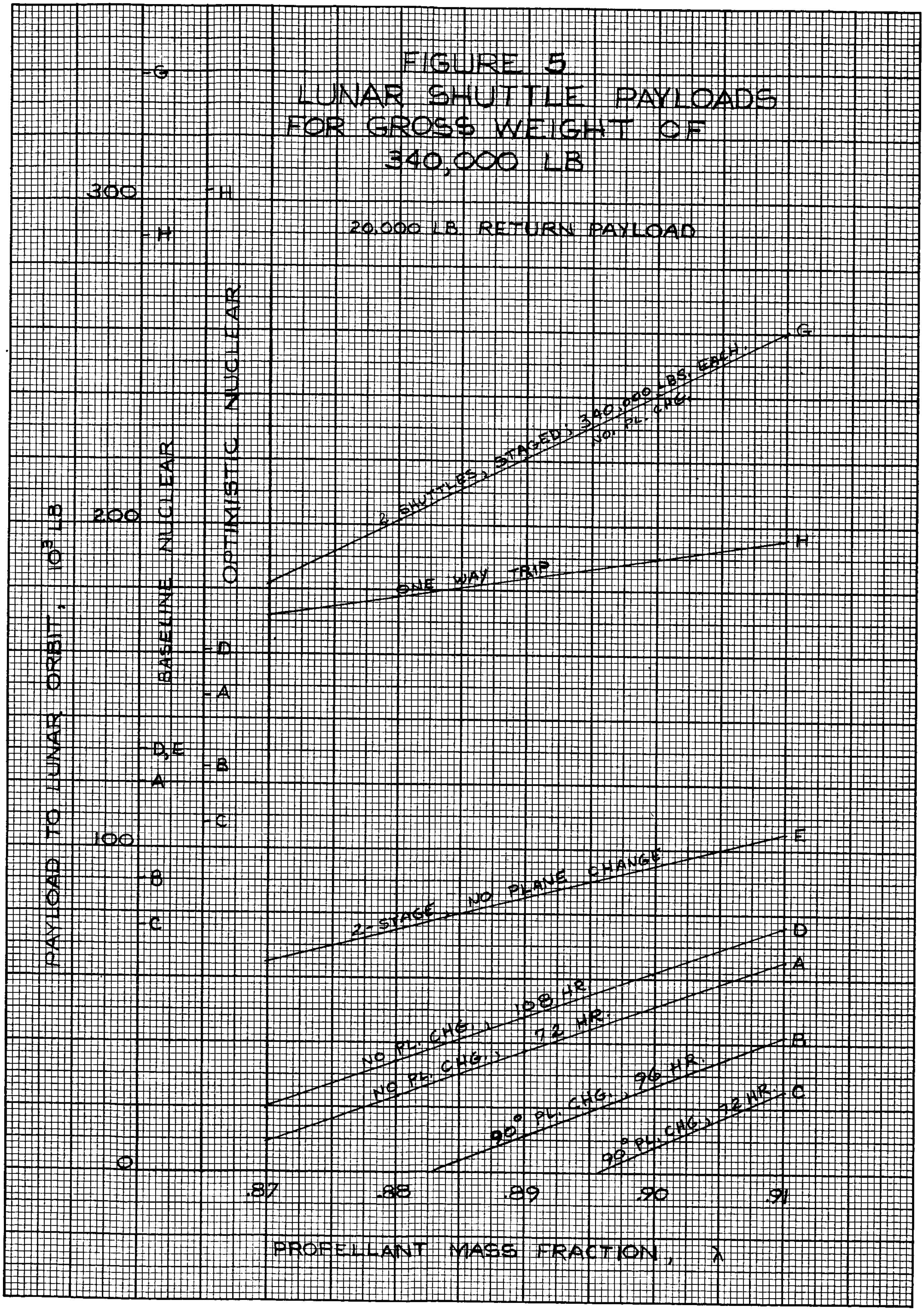
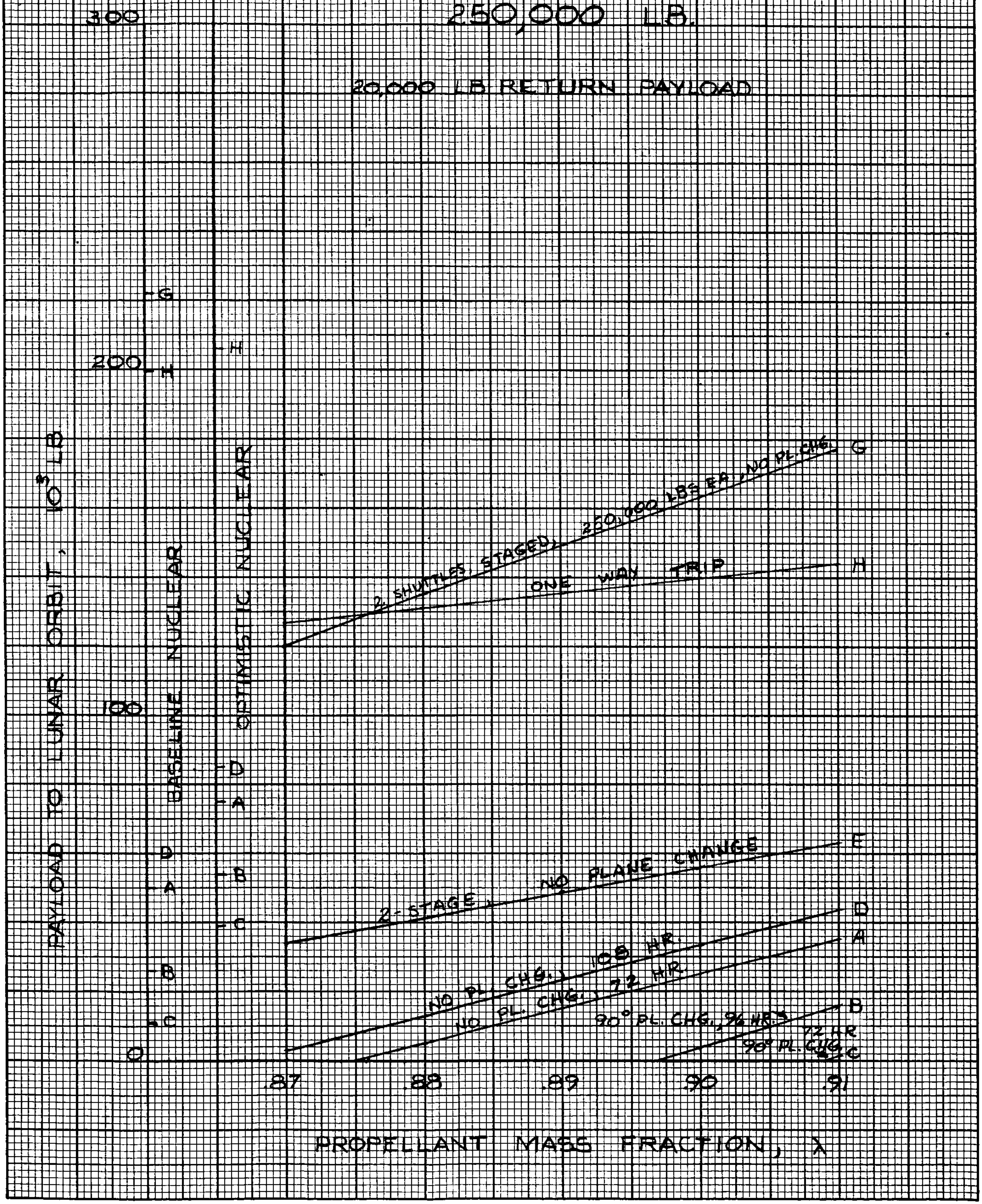


FIGURE 5
LUNAR SHUTTLE PAYLOADS
FOR GROSS WEIGHT OF
340,000 LB
20,000 LB. RETURN PAYLOAD
PAYLOAD TO LUNAR ORBIT, 10³ LB
BASELINE NUCLEAR
OPTIMISTIC NUCLEAR
300
200
100
0
2 SHUTTLES, STAGED; 340,000 LBS. EACH
NO. PL. CHG.
ONE WAY TRIP
2-STAGE, NO PLANE CHANGE
NO PL. CHG., 108 HR.
NO PL. CHG., 72 HR.
90° PL. CHG., 96 HR.
90° PL. CHG., 72 HR.
G
H
D,E
A
B
C
D
E
.87
.88
.89
.90
.91
PROPELLANT MASS FRACTION, λ

FIGURE 6
LUNAR SHUTTLE PAYLOADS
FOR GROSS WEIGHT OF
250,000 LB.

20,000 LB RETURN PAYLOAD



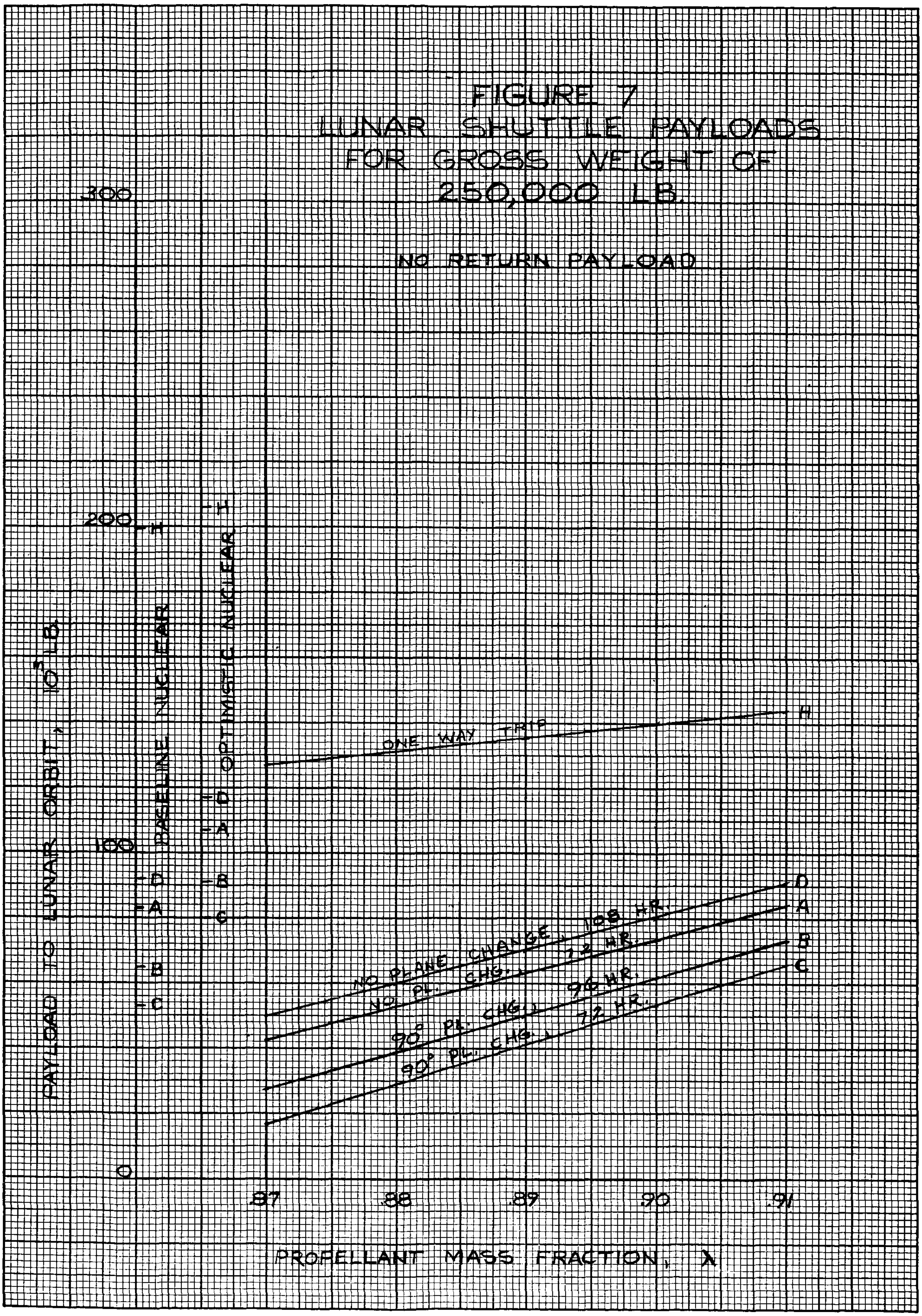


FIGURE 7
LUNAR SHUTTLE PAYLOADS
FOR GROSS WEIGHT OF
250,000 LB.

FIGURE 8
LUNAR SHUTTLE PAYLOADS
FOR GROSS WEIGHT OF
210,000 LB.

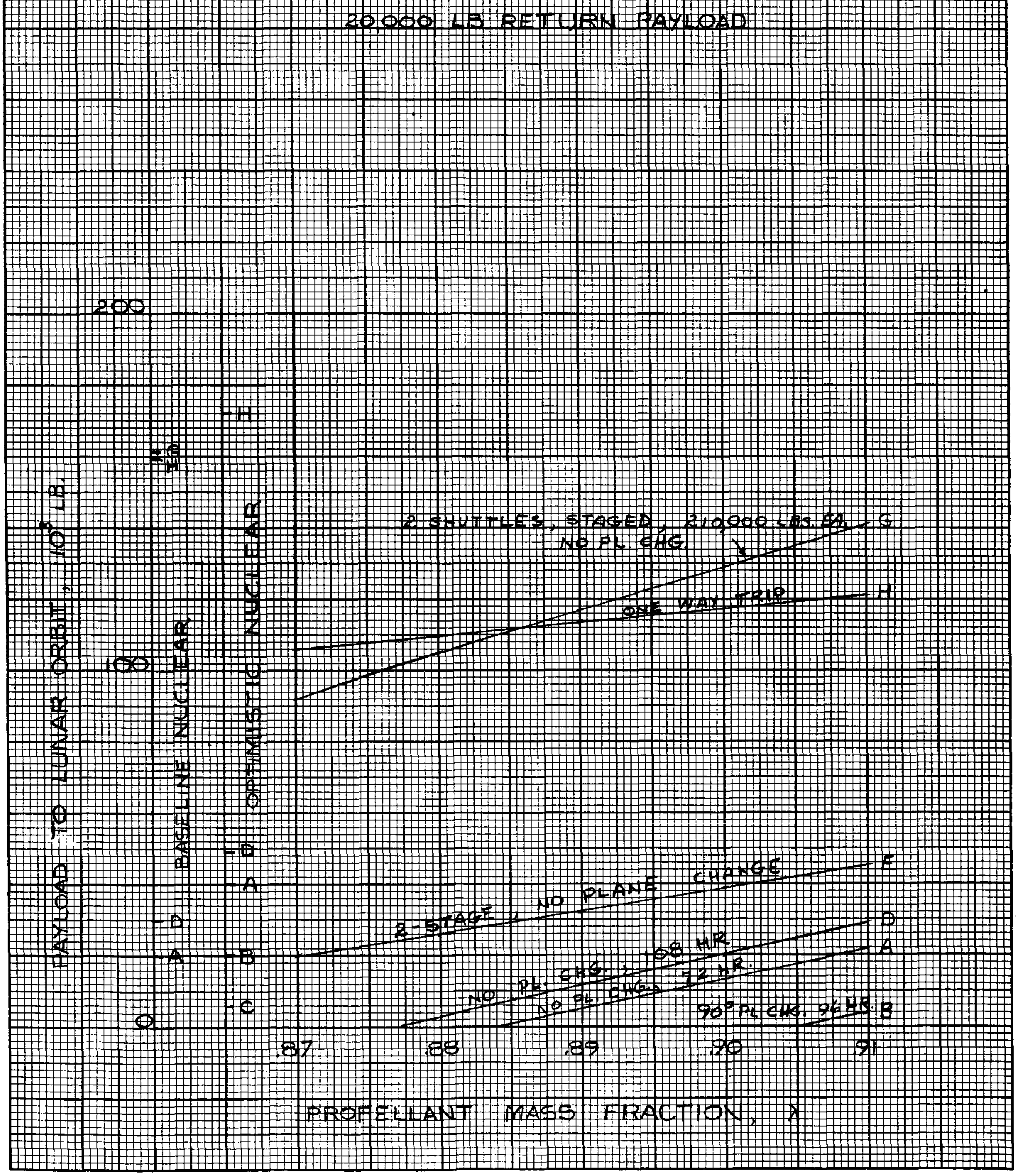
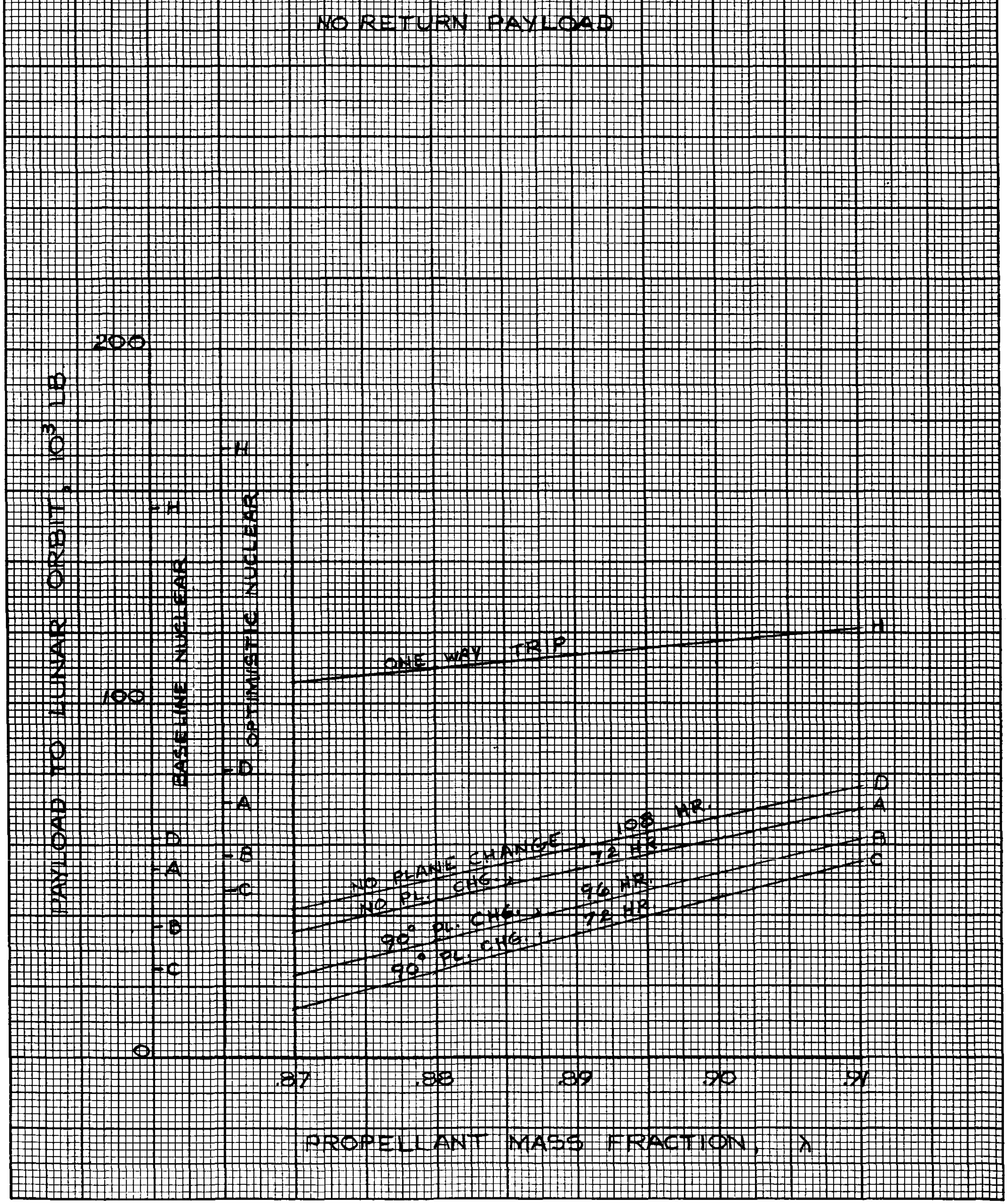


FIGURE 9
LUNAR SHUTTLE PAYLOADS
FOR GROSS WEIGHT OF
210,000 LB



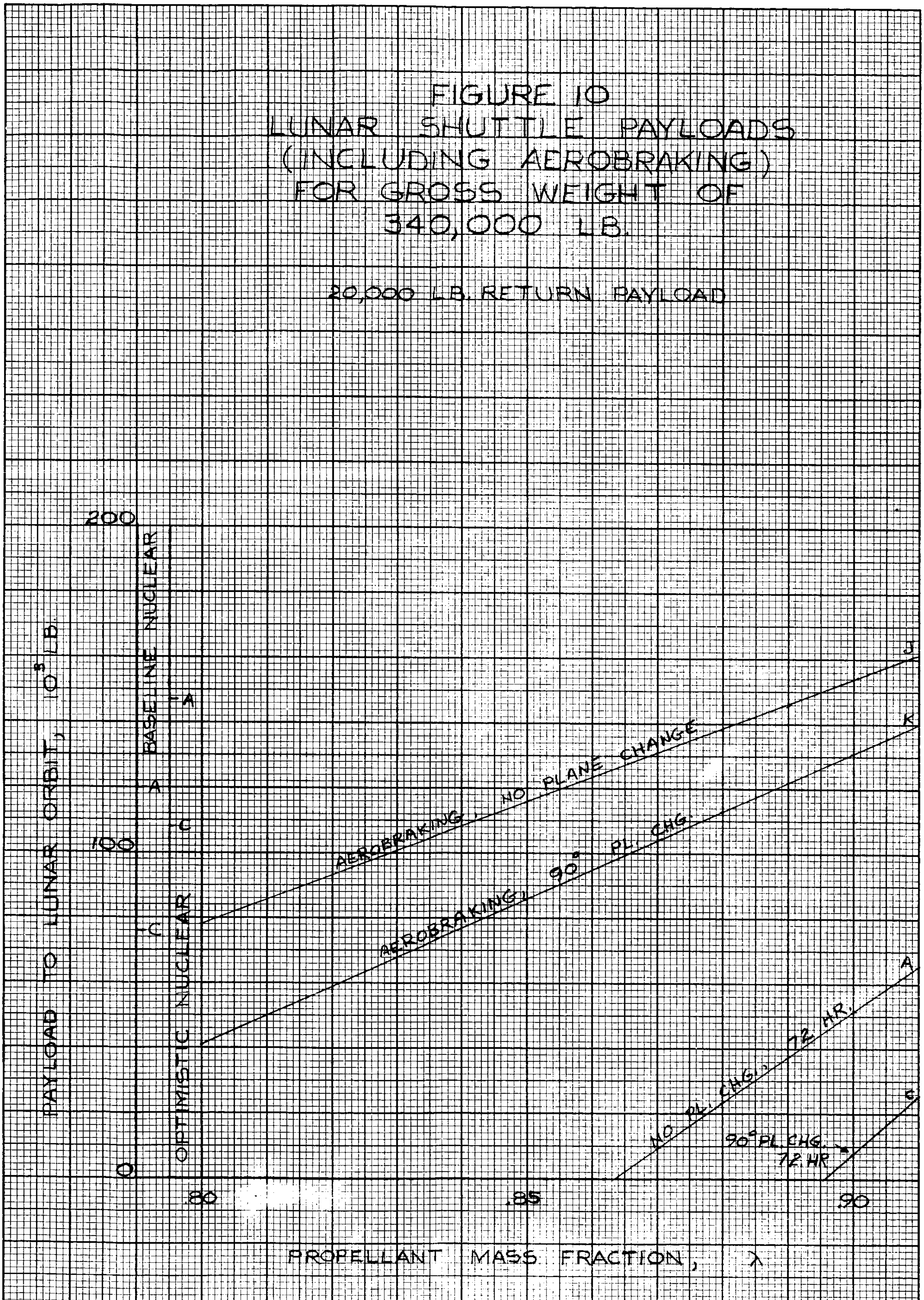


FIGURE 10
LUNAR SHUTTLE PAYLOADS
(INCLUDING AEROBRAKING)
FOR GROSS WEIGHT OF
340,000 LB.
20,000 LB. RETURN PAYLOAD
PAYLOAD TO LUNAR ORBIT, 10^3 LB.
200
100
0
BASELINE NUCLEAR
OPTIMISTIC NUCLEAR
A
C
A
C
AEROBRAKING, NO PLANE CHANGE
AEROBRAKING, 90° PL. CHG.
J
K
A
C
NO PL. CHG., 72 HR.
90° PL. CHG. 72 HR
.80
.85
.90
PROPELLANT MASS FRACTION, λ

FIGURE 11
LUNAR SHUTTLE PAYLOADS
(INCLUDING AEROBRAKING)
FOR GROSS WEIGHT OF
250,000 LB.

20,000 LB. RETURN PAYLOAD

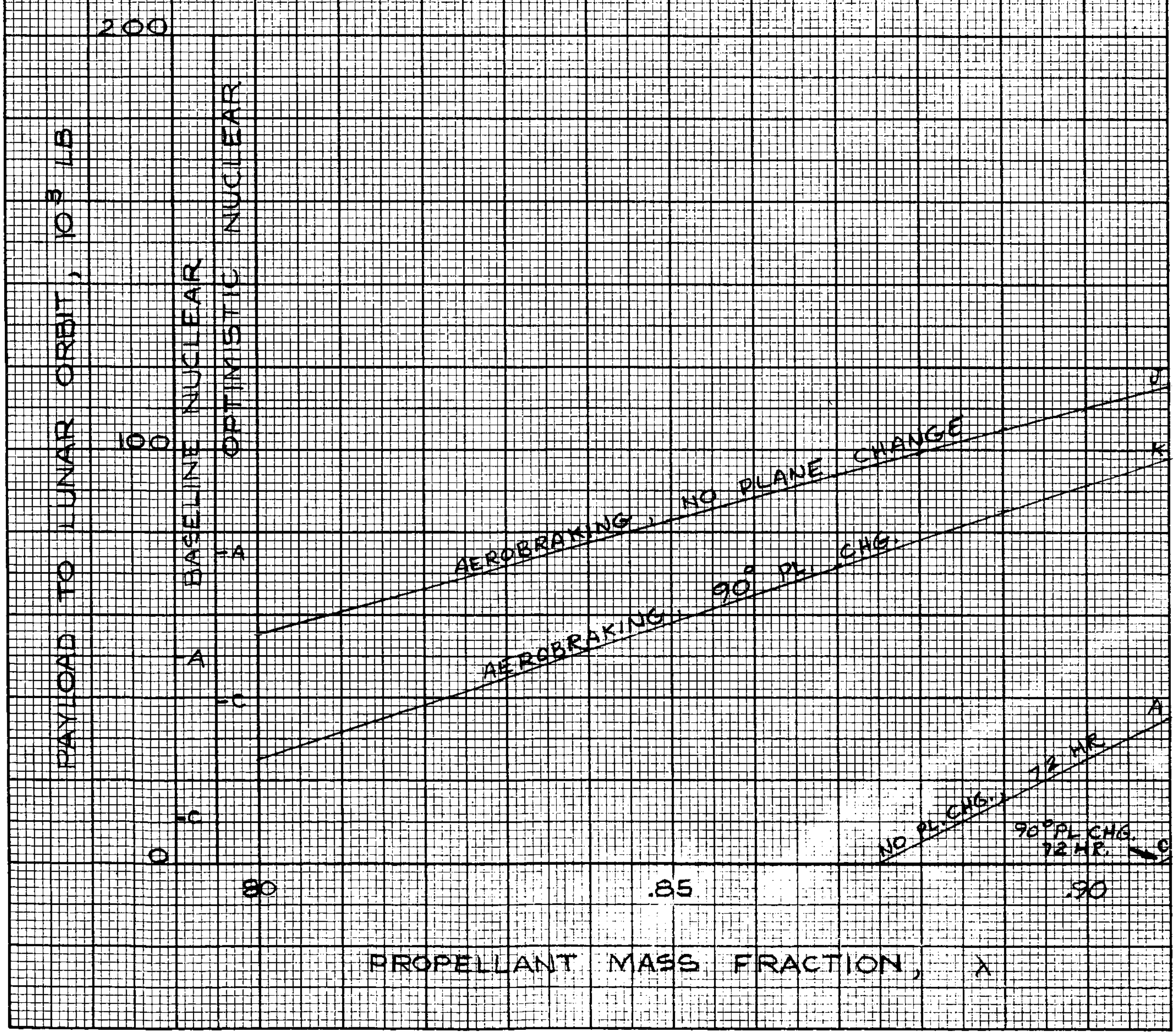


FIGURE 12
LUNAR SHUTTLE PAYLOADS
(INCLUDING AEROBRAKING)
FOR GROSS WEIGHT OF
210,000 LB.

20,000 LB. RETURN PAYLOAD